Pis'ma v ZhETF, vol. 93, iss. 12, pp. 765 – 769 

# Variation of jet quenching from RHIC to LHC and thermal suppression of QCD coupling constant

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Submitted 11 May 2011

We perform a joint jet tomographic analysis of the data on the nuclear modification factor $R_{AA}$ from PHENIX at RHIC and ALICE at LHC. The computations are performed accounting for radiative and collisional parton energy loss with running coupling constant. Our results show that the observed slow variation of $R_{AA}$ from RHIC to LHC indicates that the QCD coupling constant is suppressed in the quark-gluon plasma produced at LHC.

**1.** The discovery of strong suppression of high-$p_T$ hadrons in $AA$-collisions (usually called the jet quenching) is one of the main results from the RHIC program [1]. A similar effect has been observed in the ALICE experiment at LHC [2] for $\sqrt{s} = 2.76\,\mathrm{TeV}$. The most natural physical reason for this effect is parton energy loss (radiative and collisional) in the hot quark-gluon plasma (QGP) produced in the initial stage of $AA$-collisions. There has been much progress in the past 15 years in understanding the radiative energy loss due to induced gluon emission [3–8]. For RHIC and LHC namely this mechanism dominates the energy loss [9]. Current studies in jet quenching are motivated by its importance for jet tomography of the dense QCD matter in $AA$-collisions. Unfortunately, the available approaches to the induced gluon radiation are limited to one gluon emission. While for robust jet tomography, one should also take into account multiple gluon emission. At present multiple gluon radiation is usually accounted for in the approximation of independent gluon emission [10]. However, this approximation has no serious theoretical justification in QCD, and can lead to considerable systematic errors. Also, additional uncertainties of the jet tomography come from the unsolved problem of treatment on an even footing the radiative and collisional (which is small but not negligible) contributions.

Due to theoretical uncertainties presently the jet tomography can give only qualitative information about density of the QCD matter in $AA$-collisions at a given energy. However, one may expect that the theoretical uncertainties should not be very important for variation of jet quenching with energy. For this reason the information extracted from jet tomography based on the data at very different energies should be more robust. From this point of view it is very interesting to perform a joint analysis of the nuclear modification factor $R_{AA}$ measured at RHIC and LHC. In the present work we perform such an analysis using the data on $R_{AA}$ for Au + Au collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ from PHENIX [11] and for Pb + Pb collisions at $\sqrt{s} = 2.76\,\mathrm{TeV}$ from ALICE [2]. A major purpose of this analysis is to decide whether the variation of $R_{AA}$ from RHIC to LHC indicates that the QCD coupling constant becomes smaller in the plasma produced at LHC. The suppression of the in-medium $\alpha_s$ at LHC as compared to that at RHIC energies would be quite natural since the data on multiplicities [12–14] indicate that the initial entropy at $\sqrt{s} = 2.76\,\mathrm{TeV}$ is bigger by a factor of $\sim 2.2$ than that at $\sqrt{s} = 200\,\mathrm{GeV}$. This is translated into $\sim 30\%$ growth of the initial temperature at $\sqrt{s} = 2.76$ which should lead to a sizeable thermal suppression of $\alpha_s$. The fact that the PHENIX [11] and ALICE [2] data on $R_{AA}$ are very similar supports qualitatively suppression of $\alpha_s$ at LHC. It would be interesting to see this from a quantitative analysis.

The method of computation of the nuclear modification factor in the present work is similar to that used in [15]. We account for both the radiative and collisional energy losses. They are calculated with running $\alpha_s$ frozen at small momenta. We treat the induced gluon radiation within the light-cone path integral (LCPI) approach [4]. The collisional energy loss is viewed as a perturbation effect.

**2.** The nuclear modification factor $R_{AA}$ for a given impact parameter $b$ can be written as

$$R_{AA}(b) = \frac{dN(A + A \to h + X)/d\mathbf{p}_T dy}{T_{AA}(b) d\sigma(N + N \to h + X)/d\mathbf{p}_T dy}\,. \quad (1)$$

Here $\mathbf{p}_T$ is the hadron transverse momentum, $y$ is rapidity (we consider the central region $y = 0$), $T_{AA}(b) = \int d\boldsymbol{\rho} T_A(\boldsymbol{\rho}) T_A(\boldsymbol{\rho} - \mathbf{b})$, $T_A$ is the nucleus profile function. The differential yield for high-$p_T$ hadron production in $AA$-collision can be written in the form

$$\frac{dN(A+A\to h+X)}{d\mathbf{p}_T dy}=$$
$$=\int d\boldsymbol{\rho} T_A(\boldsymbol{\rho})T_A(\boldsymbol{\rho}-\mathbf{b})\frac{d\sigma_m(N+N\to h+X)}{d\mathbf{p}_T dy}, \quad (2)$$

where $d\sigma_m(N+N\to h+X)/d\mathbf{p}_T dy$ is the medium-modified cross section for the $N+N\to h+X$ process. Similarly to the ordinary pQCD formula, we write it as

$$\frac{d\sigma_m(N+N\to h+X)}{d\mathbf{p}_T dy}=$$
$$=\sum_i\int_0^1\frac{dz}{z^2}D^m_{h/i}(z,Q)\frac{d\sigma(N+N\to i+X)}{d\mathbf{p}^i_T dy}. \quad (3)$$

Here $\mathbf{p}^i_T=\mathbf{p}_T/z$ is the parton transverse momentum, $d\sigma(N+N\to i+X)/d\mathbf{p}^i_T dy$ is the hard cross section, $D^m_{h/i}$ is the medium-modified fragmentation function (FF) for transition of a parton $i$ into the observed hadron $h$. For the parton virtuality scale $Q$ we take the parton transverse momentum $p^i_T$. We assume that hadronization occurs outside of the QGP. For jets with $E\lesssim 100\,\text{GeV}$ the hadronization scale, $\mu_h$, is relatively small. Indeed, one can easily show that the $L$-dependence of the parton virtuality reads $Q^2(L)\sim\max(Q/L,Q_0^2)$, where $Q_0\sim 1{-}2\,\text{GeV}$ is some minimal nonperturbative scale. For RHIC and LHC, when $\tau_{\text{QGP}}\sim R_A$ ($\tau_{\text{QGP}}$ is the typical lifetime/size of the QGP phase, $R_A$ is the nucleus radius), it gives $\mu_h\sim Q_0$ (for $E\lesssim 100\,\text{GeV}$). Then we can write

$$D^m_{h/i}(z,Q)\approx\int_z^1\frac{dz'}{z'}D_{h/j}(z/z',Q_0)D^m_{j/i}(z',Q_0,Q)\,, \quad (4)$$

where $D_{h/j}(z,Q_0)$ is the vacuum FF, and $D^m_{j/i}(z',Q_0,Q)$ is the medium-modified FF for transition of the initial parton $i$ with virtuality $Q$ to a parton $j$ with virtuality $Q_0$. For partons with $E\lesssim 100\,\text{GeV}$ the typical length scale dominating the energy loss in the DGLAP stage is relatively small $\sim 0.3{-}1\,\text{fm}$ [15]. This length is of the order of the formation time of the QGP $\tau_0\sim 0.5\,\text{fm}$. On the other hand, the induced radiation stage occurs at a larger length range $l\sim\tau_0{-}\tau_{\text{QGP}}$. For this reason to first approximation one may ignore the overlap of the DGLAP and induced radiation stages at all [15]. Then we can write

$$D^m_{j/i}(z,Q_0,Q)=$$
$$=\int_z^1\frac{dz'}{z'}D^{\text{ind}}_{j/l}(z/z',E_l)D^{\text{DGLAP}}_{l/i}(z',Q_0,Q), \quad (5)$$

where $E_l=Qz'$, $D^{\text{ind}}_{j/l}$ is the induced radiation FF (it depends on the parton energy $E$, but not virtuality), and $D^{\text{DGLAP}}_{l/i}$ is the vacuum DGLAP FF.

We have computed the DGLAP FFs with the help of the PYTHIA event generator [16]. Our method of calculation of the in-medium FF via the one gluon probability distribution is described in detail in [15], and need not to be repeated here. We just enumerate its basic aspects.

- The multiple gluon emission is accounted for employing Landau's method as in [10].
- In calculating the $q\to q$ FF the leakage of the probability to the unphysical region of $\Delta E>E$ is accounted for by renormalizing the FF.
- The normalization of the FF for $(g\to g)$-transition, which does not conserve the number of gluons, is fixed from the momentum sum rule.
- We also take into account the $q\to g$ FF which is usually ignored. Its normalization is fixed from the momentum conservation for $(q\to q)$- and $(q\to g)$-transitions. Thus for quarks our FFs satisfy the flavor and momentum conservation.

We calculate the hard cross sections using the LO pQCD formula with the CTEQ6 [17] parton distribution functions. To simulate the higher order $K$-factor we take for the virtuality scale in $\alpha_s$ the value $cQ$ with $c=0.265$ as in the PYTHIA event generator [16]. We account for the nuclear modification of the parton densities (which leads to some small deviation of $R_{AA}$ from unity even without parton energy loss) with the help of the EKS98 correction [18]. For the vacuum FFs we use the KKP parametrization [19].

**3.** One gluon induced emission has been computed within the LCPI-formalism [4]. The formulas convenient for numerical computations of the induced gluon spectrum are given in our paper [20], to which the interested reader is referred. We take $m_q=300$ and $m_g=400\,\text{Mev}$ for the quark and gluon quasiparticle masses. These values were obtained in [21] from the analysis of the lattice data within the quasiparticle model for the relevant range of the plasma temperature $T\sim(1-3)T_c$. To fix the Debye mass we use the results of the lattice calculations for $N_f=2$ [22] which give the ratio $\mu_{\text{D}}/T$ slowly decreasing with $T$ ($\mu_{\text{D}}/T\approx 3$ at $T\sim 1.5T_c$, $\mu_{\text{D}}/T\approx 2.4$ at $T\sim 4T_c$). However, the results for $R_{AA}$ are not very sensitive to the Debye mass.

We evaluate the gluon spectrum with running $\alpha_s$. The details of incorporating the running coupling constant in the LCPI-formalism are described in [9]. We use parametrization of $\alpha_s$ with freezing at some value $\alpha_s^{\text{fr}}$ at low momenta. For vacuum a reasonable choice is $\alpha_s^{fr}\approx 0.7$. This value was previously obtained by fitting the low-$x$ proton structure function $F_2$ within the dipole BFKL-equation [23]. A similar value of $\alpha_s^{\text{fr}}$ follows from the relation $\int_0^{2\,\text{GeV}} dQ \frac{\alpha_s(Q^2)}{\pi} \approx 0.36\,\text{GeV}$ obtained in [24] from the analysis of the heavy quark energy loss in vacuum. In vacuum the stopping of the growth of $\alpha_s$ at low $Q$ may be caused by the nonperturbative effects [24]. In the QGP thermal partons can give an additional suppression of $\alpha_s$ at low momenta ($Q \sim 2{-}3T$). To study the role of the in-medium suppression of $\alpha_s$ we have performed the numerical computations for several smaller values of $\alpha_s^{\text{fr}}$. We are fully aware that this procedure, in which the in-medium suppression of the coupling is enforced on the average, so to speak, via modification of one parameter $\alpha_s^{\text{fr}}$ at any plasma temperature is very crude. We leave more accurate calculations with a temperature dependent parametrization of $\alpha_s$ for future work.

The collisional energy loss is small as compared to the radiative one but not negligible [9]. In the present work we treat the effect of the collisional energy loss on the nuclear modification factor as a perturbation within the method suggested in [15]. It consists in renormalization of the initial temperature for the radiative contribution to the in-medium FFs using the following equation

$$\Delta E_{\text{rad}}(T_0^{'}) = \Delta E_{\text{rad}}(T_0) + \Delta E_{\text{col}}(T_0),$$

where $\Delta E_{\text{rad/col}}$ is the radiative/collisional energy loss, $T_0$ is the real initial temperature of the QGP, and $T_0^{'}$ is the renormalized temperature. As in [15] in calculating $\Delta E_{\text{rad/col}}$ we take for the maximum energy loss half of the initial parton energy. The renormalized temperature is not very sensitive to the choice of the maximum energy loss in $\Delta E_{\text{rad/col}}$.

We evaluate $\Delta E_{\text{col}}$ within a modified Bjorken method [25] with accurate kinematics of the binary collisions (the details can be found in [9]). We use the same infrared cutoffs and parametrization of the coupling constant for the radiative and collisional energy loss, which is important for minimizing the theoretical uncertainties in the fraction of the collisional contribution.

We also included the effect of the energy gain due to gluon absorption from plasma by fast partons. It is done with the same prescription as for collisional energy loss by renormalizing the plasma temperature. However, the effect of the energy gain on $R_{AA}$ is practically negligible [15], and can be safely neglected.

**4.** We describe the QGP in the Bjorken model [26] which gives $T_0^3\tau_0 = T^3\tau$. We take $\tau_0 = 0.5\,\text{fm}$. Note that our numerical results show that $R_{AA}$ is rather insensitive to the precise value of $\tau_0$. It is physically due to the fact that induced gluon emission, dominating parton energy loss, requires typically a finite formation time which exceeds considerably the value of $\tau_0$. For a given impact parameter the entropy density has been evaluated in the Glauber model using the Woods–Saxon nucleus density with parameters as in [2], and $\sigma_{NN}^{\text{in}} = 42\,\text{mb}$ for $\sqrt{s} = 200\,\text{GeV}$ and $\sigma_{NN}^{\text{in}} = 64\,\text{mb}$ for $\sqrt{s} = 2.76\,\text{TeV}$. In calculating the entropy distribution in the impact parameter space we take it in the form $dS/dy = C[\alpha dN_{\text{part}}/d\eta + (1-\alpha)dN_{\text{coll}}/d\eta]$, where the $N_{\text{part}}$ and $N_{\text{coll}}$ terms correspond to the soft and hard mechanisms. We take $\alpha = 0.85$ obtained in the hydrodynamical simulations of $AA$-collisions in [27]. The normalization of the entropy has been fixed using the entropy/multiplicity ratio $S/N_{\text{ch}} = 7.67$ from [28]. Note that for Au + Au collisions at $\sqrt{s} = 200\,\text{GeV}$ this prescription gives the total entropy smaller by $\sim 20\%$ than that used in [27]. To simplify numerical computations for each impact parameter $b$ we calculate the in-medium FFs for a uniform distribution of the initial temperature $T_0$ which was obtained by averaging the realistic entropy distribution computed within the Glauber model. For the 0–5% centrality bin in Au + Au collisions at $\sqrt{s} = 200\,\text{GeV}$ we use $dN_{\text{ch}}/d\eta = 687$ [12], and in Pb + Pb collisions at $\sqrt{s} = 2.76\,\text{TeV}$ $dN_{ch}/d\eta = 1601$ [14]. These multiplicities give $T_0 \approx 300\,\text{MeV}$ for the central Au + Au collisions at $\sqrt{s} = 200\,\text{GeV}$ and $T_0 \approx \approx 400\,\text{MeV}$ for Pb + Pb collisions at $\sqrt{s} = 2.76\,\text{TeV}$.

The fast parton path length in the QGP, $L$, in the medium has been calculated according to the position of the hard reaction in the impact parameter plane. For $L > \tau_{\text{QGP}}$ we treat the medium as a mixture of plasma and hadron phases with relative fractions defined from the decrease of entropy density as $s \propto 1/\tau$ [26]. To take into account the fact that at times about $1{-}2$ units of $R_A$ the transverse expansion should lead to fast cooling of the hot QCD matter [26] we also impose the condition $L < L_{\text{max}}$. We performed the computations for $L_{\text{max}} = 8$ and 10 fm. The difference between these two versions is small.

**5.** In Fig. 1 the theoretical $R_{AA}$ for $\pi^0$ production in the 0–5% central Au + Au collisions at $\sqrt{s} = 200\,\text{GeV}$ computed with $\alpha_s^{\text{fr}} = 0.7$, 0.6, and 0.5 for chemically equilibrium and purely gluonic plasmas is compared to the PHENIX-data [11]. The results are presented for purely radiative mechanism and with inclusion of collisional energy loss and radiative energy gain. As was said above, the effect of the radiative energy gain on $R_{AA}$ is practically negligible. The growth of $R_{AA}$ for gluons in Fig. 1 is due to the $(q \to g)$-transition which is usually neglected. However, it does not affect strongly the total $R_{AA}$ since for $\sqrt{s} = 200\,\text{GeV}$ the gluon contribution

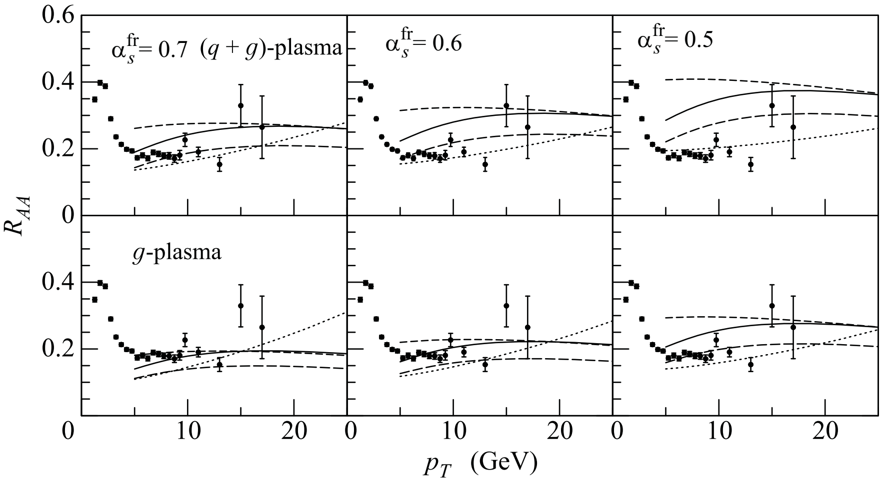


Fig. 1. The factor $R_{AA}$ for $\pi^0$ production in the 0–5% central Au + Au collisions at $\sqrt{s} = 200$ GeV for $\alpha_s^{\rm fr} = 0.7$, 0.6, and 0.5. The upper panels are for the chemically equilibrium plasma, and the lower ones for purely gluonic plasma. Solid line: the total radiative part (quarks plus gluons); dashed line: the radiative quark part; dotted line: the radiative gluon part; long-dash line: the radiative (quarks and gluons) plus collisional, and plus energy gain due to gluon absorption. The theoretical curves obtained for $L_{\rm max} = 8$ fm. The experimental points are the PHENIX-data [11]

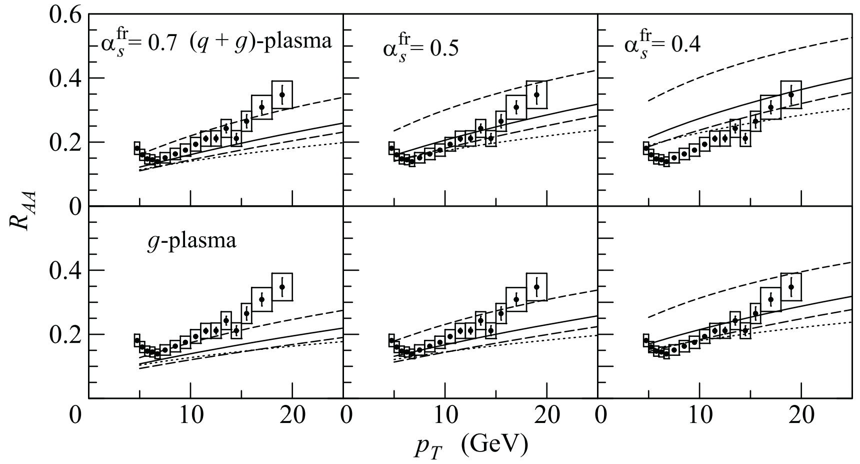


Fig. 2. The same as in Fig. 1 for the charged hadrons in Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV for $\alpha_s^{\rm fr} = 0.7$, 0.5 and 0.4. The experimental points are the ALICE-data [2], as in [2] the boxes contain the systematic errors

to the hard cross section is small at $p_T \gtrsim 15$ GeV. In Fig. 2 we compare our results for $\alpha_s^{\rm fr} = 0.7$, 0.5, and 0.4 with the ALICE-data [2] for charged hadrons in Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV.

As can be seen from Figs. 1, 2, the collisional energy loss suppresses $R_{AA}$ only by about 15–25%. For the equilibrium plasma the data for $\sqrt{s} = 200$ GeV can be described with $\alpha_s^{\rm fr} \approx 0.6-0.7$. The data for $\sqrt{s} = 2.76$ TeV agree better with $\alpha_s^{\rm fr} \approx 0.4-0.5$. It provides evidence for the thermal suppression of $\alpha_s$ at LHC due to higher temperature of the QGP. The in-medium suppression of $\alpha_s$ as the physical reason for a qualitative similarity of $R_{AA}$ at RHIC and LHC was also recently discussed in [29]. However, the effect has not been investigated quantitatively.

Note that in our previous analysis [15] of the PHENIX-data [11] the agreement with experiment was better for $\alpha_s^{\rm fr} \approx 0.5$. The difference with the present study is due to a somewhat larger total entropy of the QGP used in [15]. In [15] we used the entropy from [27]. As was said, the total entropy obtained using $S/N_{\rm ch}$ ratio from [28] is smaller by $\sim 20\%$ than that in [27]. However, this circumstance is not important from the point of view the conclusion on suppression of $\alpha_s$ at LHC, since we use the same $S/N_{\rm ch}$ ratio for RHIC and LHC.

**6**. In summary, we have analyzed the data on the nuclear modification factor obtained at RHIC in the PHENIX-experiment on Au + Au collisions at $\sqrt{s} = 200$ GeV [11] and at LHC in the ALICE-experiment on Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV [2]. The PHENIX-data may be described in the scenario with chemically equilibrium plasma without (or small) in-medium suppression of $\alpha_s$. However, the data on $R_{AA}$ from ALICE, which are qualitatively similar to that from PHENIX, agree better with the results for $\alpha_s$ smaller by $\sim 20-30\%$ than that obtained from the PHENIX-data. Thus, a relatively slow variation of $R_{AA}$ from RHIC to LHC energies indicates that the QCD coupling constant becomes smaller in the hotter QGP at LHC.

I am grateful to Jacek Otwinowski for providing me with the ALICE-data shown in Fig. 2.

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